Chapter 6
Assessing Human Control on Planform Modification over Floods: A Study of Lower Mahananda–Balason River System, India

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Abstract An indicator-based assessment, using five indicators each on anthropogenic interventions and channel planform, for three major flood events in 1968, 1993, and 2017, was carried out to identify the predominance between floods and human activities in modifying the planform of the Mahananda-Balason system (MBS). Initially, the unconfined stretches of the studied system were segmented into 20 equidistant reaches and used as the assessment units. The land use/land cover practices of the study region were classified using the support vector machine algorithm. The impact of human activities on channel planform was quantified through panel data regression. Planform attributes, measured for pre- and post-flood for the selected years, were tested using the two-tailed "t-test." A total of four cross-sections were measured, and the flood level of 1968 was superimposed to assess if that level of discharge can cause flooding or not. Results showed that built-up areas had expanded by 197.85% during these 49 years, for the entire area, at the expense of agricultural land or grassland and river. Accordingly, embankments were increased from 2.63% in 1968 to 51.85% in 2017, and almost the entire channel bed (82%) was experiencing large-scale sediment extraction, and significant portions of the adjoining floodplain were concretized (24.10%). Following that, CA, CW, CL, and BI were reduced significantly by $\geq 40\%$. The reduction of CCB was also significant but relatively lower in percentage (10.69%). All these fluctuations in channel planform properties were well explained by anthropogenic interventions since the R^2 values were measured >0.70 indicating a strong correlation between the anthropogenic interventions and channel planform alterations. Increased human activities had impacted the channel planform in such a way that except in 1968, no significant inter-seasonal fluctuations regarding channel planform were measured. In few reaches, planform properties responded to the occurrence of floods in 1993 and 2017. Conversely, several reaches even experienced channel narrowing after the flood discharge. Embanking was done on such a large scale that in most areas, even

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the flood levels of 1968 could not overtop it. Coupled effect of these anthropogenic interventions is transforming this river system into a controlled one where natural channel forming factors have limited roles in reshaping channel planform, which in return is causing socio-hydrological hazards in the form of undersupply of sediments, lack of groundwater, and destabilization of bridges. This cost and time effective methodology can be adopted in other rivers also to assess the extent of anthropogenic interventions and planform alteration along with identifying the responsible factors behind the planform adjustment; however, more in-depth and long-term study is required to fully understand the interrelationship among the anthropogenic interventions and change in channel planform.

Keywords Anthropogenic interventions · High flood level · Planform alterations · Sub-Himalayan foothills

1 Introduction

Channel planform, the function of a complex interplay between water and sediment discharge, is eventually modified by natural phenomena such as floods, tectonic movement, glacial outbursts, and landslides (Benda et al., 2003; Kiss & Blanka, 2012 Scorpio & Rosskopf, 2016; Righini et al., 2017). Among these, flood is the most predominant since it is the most frequent event which actively influences the fluctuation of sediment and water discharge, but in this era of Anthropocene, anthropogenic activities are becoming predominant in short-term channel planform adjustment (Bandyopadhyay & De, 2017; Bhattacharya et al., 2019). These anthropogenic activities or human modifiers of channel planform can be grouped into some active and passive modifiers. Longitudinal alterations in the form of dams, barrages, retention dams, and sediment mining from channel beds are among the modifiers that directly alter the fluctuation of water and sediment flow (Kondolf, 1994; Kondolf, 1997). On the other hand, lateral disconnection, increase in imperviousness, and removal of vegetation cover can be termed as passive modifiers since these trigger the fluctuation of sediment and water flow by altering the overland flow (Chin & Gregory, 2005; Gregory, 2006; Comiti et al., 2011). At present, the large rivers, especially in Southeast Asia, are undergoing tremendous degradation regarding their hydromorphological properties, hydro-chemical characteristics, and biota assemblage as well (Pamayotou, 1993; Douglas, 1999; Best, 2019; Macklin & Lewin, 2019; Liu et al., 2020). Large-scale flow regulation by damming, embanking, and channelizing along with extensive sediment mining from channel bed is reconfiguring the channel planform at an alarming pace. Rapid urbanization, in this twenty-first century, along the river banks by eliminating the natural floodplain features and vegetation cover, has intensified this process (Paul & Meyer, 2001; Chin, 2006). In response to that channel, the planform is reshaping in such a way that it could bring enormous socio-hydrological hazards such as lowering of groundwater, undersupply of water, sediments and biota, lowering of the channel bed, destabilization of bridge pillars, embankment, etc. (Gregory, 2006; Biswas, 2018).

Channel planform, altered by natural factors, can quickly regain its previous equilibrium condition, but if the anthropogenic activities take part in the reshaping process, then it would create noticeable obstacles in regaining its intrinsic physiography (Kiss & Blanka, 2012; Khaleghi & Surian, 2019). The natural channel-forming factors such as floods are not a day-to-day phenomenon; it occurs once or a few times annually, whereas human activities can be experienced relentlessly with a continuous increase in intensity. Presently developed engineering techniques and river management activities have significantly mitigated the flood hazards by halting and regulating the suddenly increased discharge (Chandra, 2003; Sen, 2010; Abbas et al., 2016; Mohanty et al., 2020). Dams and barrages are used as the major tools of such flood control. Channel planform modification induced by flood discharge can also be overwhelmed by other human activities, such as deforestation, urbanization, and lateral disconnection; sediment extraction can also become the major channel-forming factor.

India being a developing country in Southeast Asia is also not exempted from these intensified anthropogenic interventions on rivers and their effects on channel planform. The massive infrastructural developments started in the 1990s have noticeably modified the country's river-dominated landscapes (Siddiqui, 2010; Mukherji, 2013; Das, 2015). Similarly, such urbanization, channelization, embanking of the river banks, and sediment extraction from channel beds have become a serious issue for the rivers of sub-Himalayan foothills also. Sub-Himalayan foothill, popularly known as "Terai," is presently undergoing a large-scale land use transformation (Prokop & Sarkar, 2012; Prokop, 2018). For ages, rivers were getting modified by human activities, but the rate of such has increased manifold during the last decade. After the adoption of new economic reforms in 1991, this region, sharing boundaries with Nepal, Bhutan and China, serving as a gateway to north-east India has gained immense economic potential, which ultimately results in massive infrastructural development. With this, large-scale immigration, not only from the neighboring states but also from the countries as well, followed by unplanned urbanization became inevitable (Ghosh, 2018). In response to this, the rivers of the "Terai," characterized by heavy monsoon discharge, wide gravelly beds, and braided channel patterns are experiencing notable adjustments toward narrowing, lowering, and becoming single-threaded sinuous rivers (Mitra et al., 2020). Siliguri, the largest urban center of the "Terai" of West Bengal, is situated at the banks of Mahananda and Balason (M and B), immensely pressurizes the adjoining river system. Mostly, the unconfined stretches of these rivers are affected as the topographical hindrances of the hills have restricted the intense human activities only to the floodplain. Since the area receives ample rainfall (2500 mm) from May end to early November, and no major longitudinal obstructions are there, hence heavy flood discharge is inevitable. The largest flood in the recent times of this region occurred in October 1968, and from then onwards numerous major flood events were witnessed in this region (Roy, 2011). But despite having such dominance of floods, the channel planform exhibits no intent of regaining its intrinsic channel planform. Ecologically sensitive and geomorphologically unique sub-Himalayan river systems are an integral part of that landscape, which provides

numerous ecosystem services; now excessive human control would reduce the resources' potentiality, which will ultimately affect all kinds of stakeholders of this river system. In this regard, recently several studies on the rivers such as Teesta, Torsa, Kaljani, Jaldhaka, and Chel Rivers have assessed the planform adjustment scenario (Ayaz et al., 2018; Biswas & Banerjee, 2018; Saha & Bhattacharya, 2019; Dhali et al., 2020; Hasanuzzaman et al., 2021; Saha & Bhattacharya, 2021). But surprisingly, such studies on the channel planform of the Mahananda-Balason system (MBS), which experiences one of the most intensive human activities in this region, are still due. Now to fulfill that research gap, this study was formulated with the prime objectives:

- To quantify the nature and intensity of anthropogenic alterations and channel adjustment and to assess the relationship between them.
- To analyze if the flood discharge is significantly modifying the channel planform or not.

Responsibility of floods, in channel planform modification, is predominant; however, considering the ongoing intensive human alterations, this study has further tested this notion in the unconfined stretch of the MBS.

2 Database and Methodology

2.1 The Spatiotemporal Framework Selected for This Study

The MBS can be divided into two segments from the geomorphological perspective, i.e., the confined rugged hilly region and the unconfined gently slopped floodplains. The debouching points of M and B at Gulma and Dudhia, respectively, mark the boundary between these two segments. The topographic characteristics eventually determine the intensity of human activities, since hilly rugged topography offers relatively lower accessibility and, therefore, experiences lesser human interventions. Hence, the anthropogenic activities, mostly restricted to the floodplains, extending between the debouching points to Naukaghat (26°40′ N to 26°50′ N and 88°12′ E to 88°28′ E), are selected for the study. Delineation of the study area began with the demarcation of the mountain front, a clear dividing line between the confined and unconfined areas. Following that, the unconfined floodplain having the highest and lowest elevation of 300 m and 114 m and a 244.2 km^2 of areal coverage was delineated by processing the digital elevation map (DEM) in ArcGIS (Fig. 6.1). The selected study region, characterized by gentle slopping, covered with thick quaternary deposits, is dissected by wide, multi-threaded rivers namely Mahananda, Balason, Rakti, Rohini, and several other small tributaries (Sarkar, 1989; De, 1998). Annually, the region receives heavy rainfall of over 250 cm, resulting in high monsoonal discharge and sediment yields (Gansser, 1964; Sarkar, 1989; De, 1998; Tamang, 2013; Roy, 2011). Apart from the rivers, this floodplain region is mostly covered by the urban agglomeration of the Siliguri urban region, along with ten
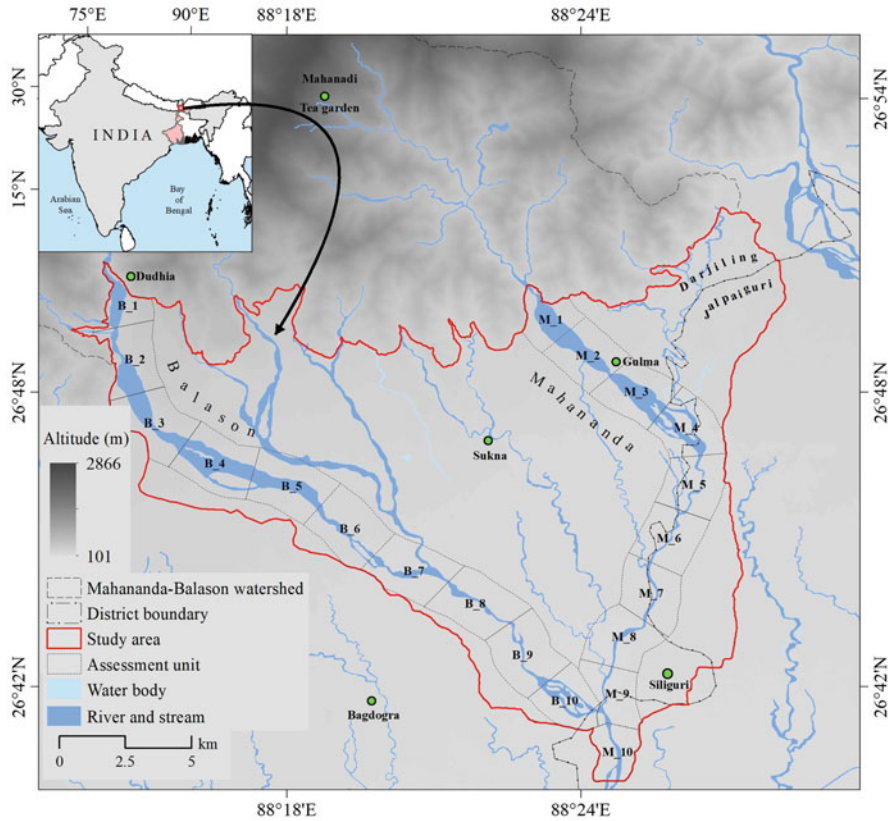
Fig. 6.1 The location of the study area, its altitude, drainage network, and segmented reaches. (Figure prepared by the author)

census towns (CTs) and several larger villages, tea gardens, dense vegetation patches, and fallow land (Census, 2006, 2014a, b).

Usually, the rivers of the "Terai" of West Bengal experience massive flood discharges annually. High, concentrated rainfall from June to October along with runoff coming from the hills is primarily responsible for this. The first documented flood event in this region occurred in 1787, resulting in the massive avulsion of Teesta (Roy, 2011). Afterwards, during 235 years (1787–2021), this region had witnessed several devastating floods. Now to comply with the data availability, this study was constrained to only the last 49 years (1968–2017). The 1968 flood was the most devastating and well-documented flood event, witnessed by the "Terai" in the last century (Sen, 2011). The flood level of 1968 is marked as the high flood level (HFL) for the rivers of this study area (Table 6.1). Afterwards, in 1993, 25 years later, another high flood discharge was experienced due to heavy rainfall in Bhutan-Darjeeling Himalaya induced by a cloud burst. Very recently in 2017, 24 years later, another heavy flood was observed, affecting almost 4 million people in northern

Table 6.1 Selected flood events for this study, their levels and cause of flooding

| Years | Flood levels (m) | | Cause | Date of peak flood discharge | References |
	M (Airview)	B (Matigara)			
1968	117.05	124.31	Cloud burst over the sub-Himalayan West Bengal and 1200 mm rainfall triggered a massive landslide and channel blocking. Continued rainfall ultimately breached those blocks and water with a high sediment load caused enormous flooding	02/10/1968	Roy (2011)
1993	114.70	NA	Cloud burst over the lower Bhutan and Darjeeling Himalaya	20/07/1993	Roy (2011) and Government of West Bengal (1993)
2017	115.60	NA	A high amount of rainfall over the sub-Himalayan West Bengal	12/08/2017	Government of West Bengal (2017)

West Bengal and Bihar (Kundu, 2017; The Times of India, 2017; State IAG-West Bengal, 2017). During this time, several other floods had occurred in 1980, 1998, 2000, 2003, 2007, and 2013, but they were either of relatively lower magnitude or distant events from the study area (Roy, 2011). Therefore, three major flood events of the study region, i.e., 1968, 1993, and 2017, having an interval of nearly 25 years were selected for this study.

This indicator-based assessment was initiated after the segmentation of both the major rivers, i.e., M and B into 20 equidistant reaches having a length of 2.25 km and 2.60 km, respectively (Goswami et al., 1999). Their adjoining floodplains, demarcated with a 1 km buffer on each bank, were characterized by dense forest, tea gardens in the upstream, and conversely extensive urban areas, fallow lands, the downstream. The reaches of M and B were denoted as M1, M2........M10 and B1, B2.......B10, respectively.

2.2 Dataset Procurement and Preprocessing

This multi-temporal study incorporated four multispectral and two panchromatic satellite images with varying spatial and temporal resolutions (Table 6.1). At first to delineate the floodplain ALOS PALSAR DEM of 12.5 m spatial resolution, dated

Table 6.2 Geospatial dataset used in this study

Season	Satellite ID	Sensor	Date of acquisition	Path/row	Resolution (m)
Preflood	CORONA	–	06-02-1968	–	1.83
	Landsat 5	TM	02-03-1993	139/041	30
	Sentinel 2A	–	02-04-2017	T45RXK	10
	Landsat/Copernicus[a]	–	05-03-2017	–	–
Post-flood	CORONA	–	22-12-1968	–	1.83
	Landsat 5	TM	15-12-1993	139/041	30
	Sentinel 2A	–	26-12-2017	T45RXK	10
	Landsat/Copernicus[a]	–	13-12-2017	–	–

[a]Acquired from the Google Earth platform

11/02/2009 was downloaded from https://asf.alaska.edu. Thereafter, three pre-monsoon images and three post-monsoon images from 1968, 1993, and 2017 were freely downloaded from https://earthexplorer.usgs.gov/ (Table 6.2). All the geo-rectifications and radiometric corrections were performed afterwards. Rigorous field surveys were carried out from February 2017 to April 2018 for understanding the nature and extent of anthropogenic activities and ground verifying the results derived from image analysis. At that time, four cross profiles across M and B were measured using Leica TC-805 total station. During the field survey, 66 persons, residing adjacent to the rivers for more than 10 years and who had a close association with these rivers, were communicated regarding the past conditions of the rivers along with the ongoing anthropogenic activities and associated adjustments in channel planform. The interviewed persons were mostly the sediment mining labors, fishermen, and the local populace. Besides this, data related to sediment extraction, and embankments were procured from the District Land Reforms Office (DLRO) of Darjeeling District and the office of the Irrigation and Waterways Department, Siliguri Division, Government of West Bengal. The previous research works, governmental reports, news reports, and blog posts were also taken into consultation to develop an understanding of the past floods that occurred in the study area. All the geo-rectification and image classification were done in QGIS 3.16 and ENVI 5.3; the entire geospatial analysis was done in ArcGIS 10.3.1, and the statistical analyses were carried out using R studio.

2.3 LULC Classification

Preprocessed satellite images of 1993 and 2017 were classified to obtain the land use/land cover (LULC) using the support vector machine (SVM) algorithm (Mondal et al., 2021). The image of 1968 could not be classified due to its panchromatic nature; therefore, manual digitization was performed. To perform this, intensive fieldwork was carried out in February 2017 to identify the land use practices of the studied region. Based on that, five classes, namely vegetation, river, tea garden, open

land, and built-up, were selected as LULC classes of 1968. For the images of 1993 and 2017, the open land was further classified into agricultural land and fallow land. Since an ambiguity was arisen in separating the agricultural areas with crops and without crops, therefore, to avoid an erroneous result, these two classes were merged in 1968. For accuracy assessment, 156 ground control points (GCP) were collected for seven classes (higher numbers of GCPs were collected for built-up and vegetation) using handheld Garmin e-Trex 20 GPS and Google Earth. Finally, using these GCPs, user's accuracy, producer's accuracy, and Kappa coefficient were calculated (Sarkar & Islam, 2020). Afterwards, the class-wise areal coverage and the temporal changes among them were measured.

2.4 Formulation and Measurement of the Indicators

A total of ten indicators (Table 6.3), grouped into two sets of five indicators each, were formulated to estimate the extent of human interventions and the dynamicity of the planform attributes. Thorough ground verification was carried out afterwards and along with it; personal interviews, literature, governmental reports, and high-resolution satellite images of CORONA and Google Earth were consulted. The indicators were formulated to measure anthropogenic interventions mostly focused on measuring the extent of lateral disconnection, in-channel sediment extraction, land use transformation, and longitudinal alterations. On the other side, the indicators measuring the planform attributes were concentrated on changing channel morphology and channel pattern. The measurements of the anthropogenic interventions were solely done from the images of the post-monsoon season, but the planform attributes were measured from both pre- and post-monsoon images to

Table 6.3 The indicators selected for this study

Indicators		Equation
Anthropogenic interventions	EM (%)	$\dfrac{\text{Length of the embanked river banks}}{\text{Total length of the banklines}} * 100$
	SM (%)	$\dfrac{\sum \text{Numbers of mined sub reaches}}{\text{Total number of sub reaches}} * 100$
	BA (%)	$\dfrac{\text{The area under built\_up of a reach}}{\text{Total area of the adjoining floodplain of that reach}} * 100$
	VA (%)	$\dfrac{\text{The area under vegetation cover of a reach}}{\text{Total area of the adjoining floodplain of that reach}} * 100$
	CS (structures/km)	$\dfrac{\text{Number of crossing structures in a reach}}{\text{Total length of that reach}}$
Channel planform	CA (km^2)	Total area of the channel corridor of a reach
	CW (m)	$\dfrac{\sum \text{Width measured}}{\text{Total number of observation}}$
	CL (km)	Total length of the channels in a reach
	CCB (%)	$\dfrac{\sum \text{Area covered by the bar in the channel of a reach}}{\text{Total area of the channel of that reach}} * 100$
	BI	$\dfrac{2(\sum \text{Length of all the islands and bars in a reach})}{\text{Total length of the reach}}$

obtain the impact of flood discharge on channel planform. Due to the lack of previous data, channel hydrology was not included in this study.

The quantification of the anthropogenic indicators started with measuring the lateral obstructions in the form of the percentage of the embanked river bank in a reach (EM). All the embankments were initially measured from the geospatial dataset, and thereafter, percentage was calculated (Huang et al., 2019). However, to quantify the embankments of 1993, secondary data, collected from Irrigation and waterways department, were used. The measurement of the reach under active sediment extraction (SM) was initiated by further subdividing the reaches into five equidistant sub-reaches. Now, the mining/extraction activities were traced sub-reach-wise from the geospatial database, literature, and personal interviews, and ultimately, the percentage of sub-reaches identified with active in-channel sediment extraction was calculated (Rinaldi et al., 2005). After covering the aspects of lateral obstruction and sediment extraction, two separate indicators measuring the percentage of built-ups in the adjoining floodplain (BA) and the percentage of vegetation cover in the adjoining floodplain (VA) were quantified to assess the intensity of land use transformation (Chin & Gregory, 2005; Kang & Marston, 2006; Keen-Zebert, 2007; Comiti et al., 2011; Del Tánago et al., 2015). These land use practices control the channel planform adjustments by fluctuating the runoff and sediment load. Now, the reach-wise areal coverages were obtained from the previously classified images, and following that, the percentages of those areal coverages were calculated. It was observed that significant longitudinal obstructions were absent in this study area, but structures altering longitudinal connectivity in the form of bridge pillars were often identified. Therefore, the intensity of these alterations was measured as the occurrence of urban crossing structures on the river channel per km (CS) (Rinaldi et al., 2013). These crossing structures alter the channel in two ways: firstly, its pillars and piers obstruct and deflect the flow, and secondly, it increases accessibility, which ultimately resulted in increasing settlements or impervious surfaces. The crossing structures were primarily identified from the satellite images, and then, the density of them was measured per kilometer of channel length.

Before starting the quantification of the planform attributes, the bank lines were digitized from all six images, and depending on the digitized bank lines, the reach-wise channel area (CA) and reach-wise mean channel width (CW) were calculated. For CW, bank-to-bank channel width was measured at every 50 m interval and thereafter averaged reach wise (Surian, 1999; Galster et al., 2008; Rinaldi et al., 2013; Scorpio & Rosskopf, 2016; Yousefi et al., 2019). Now within the digitized bank lines, all the channels and bars were measured as the total length of the channels in kilometer (CL) and areal coverage of bars in percentage (CCB) (Hajdukiewicz & Wyżga, 2018). Afterwards, to analyze the channel pattern, the braiding index (BI) after Brice (1964) was calculated reach wise. For this, the lengths of the reaches were measured midway between the banks in the channel belt, and similarly, the length of the islands and bars were also measured following its longest axis (Leopold & Wolman, 1957; Ferguson & Werritty, 1983; Ashmore, 1991; Friend & Sinha, 1993; Goswami et al., 1999; Bertoldi et al., 2009).

During all of these measurements, no data gap was observed. The changes measured through these indicators were further statistically tested using a two-tailed T-test with at least a 95% confidence interval. At the time of testing, the channel planform data from post-monsoon was taken into consideration.

2.5 Assessment of the Impact of Flood Discharge on Channel Planform

The impact of flood discharge on channel planform was assessed by analyzing the seasonal measurements of channel attributes. Those seasonal measurements were further statistically tested using a one-tailed T-test with at least a 95% confidence interval (Nandi et al., 2020). The null hypothesis of this testing was fixed as there was no difference between pre- and post-flood conditions of channel planform attributes. Now, this test was performed three times (1968, 1993, and 2017) for the entire system and for the M and B Rivers separately to identify any inter-river variations. Furthermore, the high flood levels (HFL) of both these rivers (1968 flood levels are the HFL in this region) were superimposed in the present cross-sections to understand if such floods possess any chance of flooding the adjoining areas or not. The HFLs were measured from the bridge pillars and used in superimposition.

2.6 Estimating the Relationship Between the Anthropogenic Intervention and Planform Properties

Since the structure of the data had spatial and temporal resolution, therefore, panel data regression was opted to measure the impact of the anthropogenic intervention on channel planform. It is found suitable as it deals with heterogeneous datasets and gives a standard effect in longitudinal data. For this study, a fixed effects model (FE) was used for regression analysis (Galvao Jr., 2011; Makuta & O'Hare, 2015) using the following equation:

$$y_{it} = \beta_1 X_{it} + \alpha_i + u_{it} \qquad (6.i)$$

where α_i ($i = 1 \ldots n$) is the unknown intercept for each entity (n entity-specific intercepts) and Y_{it} is the channel planform properties, where i = entity and t = time. X_{it} represents one indicator of anthropogenic intervention, β_1 is the coefficient for that indicator measuring anthropogenic interventions, and u_{it} is the error term.

The selection of the fixed effects model was backed by the Hausman specification test, which confirmed the suitability of the FE model over RE (Random Effects). This model helps to understand the relationship between the multiple dependent and independent variables within an entity on a longitudinal scale. The analysis was

primarily performed for the whole system, but to obtain an inter-system comparative assessment, the analysis was repeated for M and B separately as well. This assessment incorporated the measurements of the post-monsoon for both groups of indicators.

3 Results

3.1 Spatiotemporal Dynamics of LULC

The LULC classification (Fig. 6.2) has identified an intense urbanization process in the studied region over the past 49 years. While, in 1968, the urban region was confined to a small pocket in the southern part of the study area (M8 and M9 reach),
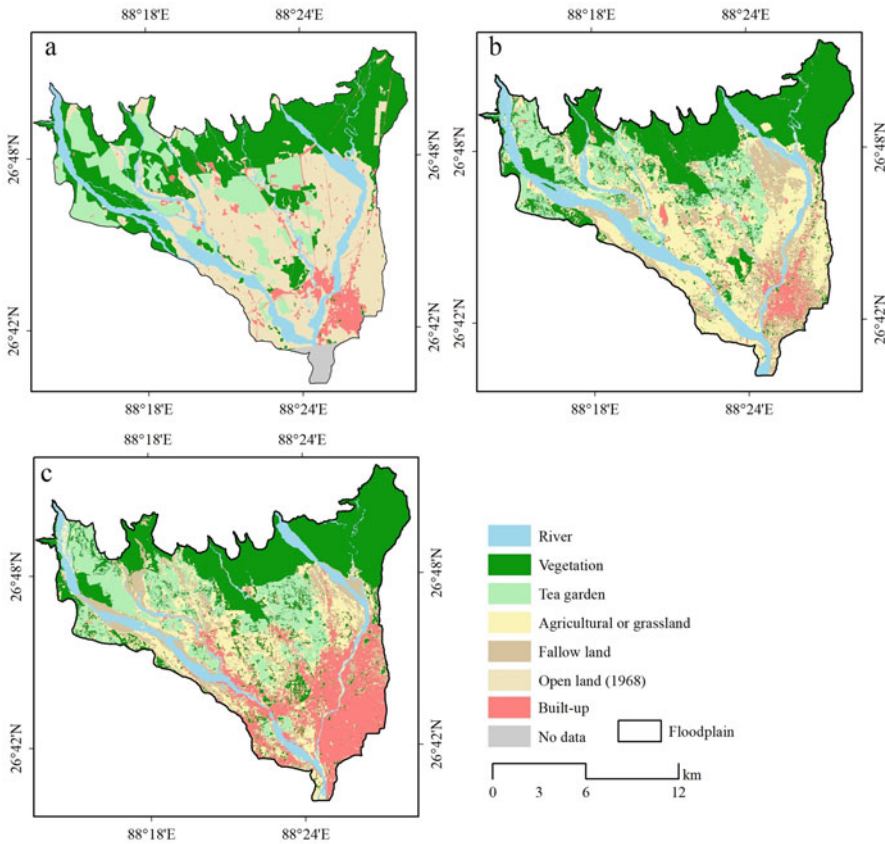

Fig. 6.2 LULC of the studied system; (**a**) 1968, (**b**) 1993, and (**c**) 2017. (Figure prepared by the author)

Table 6.4 Areal coverage and change detection data of LULC types

LULC	Areal coverage (%)			Change (%)	
	1968	1993	2017	1968–93	1993–17
River	12.34	11.87	7.79	−3.80	−34.34
Vegetation	30.89	29.76	29.63	−3.67	−0.43
Tea garden	14.64	12.88	15.47	−11.99	20.03
AG/GL (OL^{1968})	34.47	25.65	17.03	7.74	−33.59
Fallow land		11.49	12.06		4.95
Built-up area	6.05	7.35	18.02	21.49	145.17

AG/GL, agricultural land or grassland and OL^{1968}, open land for 1968

it was gradually expanded upward and acquired almost one-fifth (18.02%)
(Table 6.4) of the study area by 2017 (the areas of M5 to M10 and B7 to B10).
The overall increase (1968–2017) of built-ups during the entire study period was
estimated at 197.85%, which was mostly accelerated in the second half (1993–2017)
with an increase of 145.17%. The reduction of riverine landscape and agricultural
land had fueled this growth as they lost their areal coverage by 36.87% (1968–2017)
and 33.48% (1993–2017), respectively. A notable 34.34% reduction of the river was
estimated during the second half, which was almost ten times higher than that of the
first half. The reduction of channels was mostly observed in B4–B7 and B10 along
with M3–M6. Conversely, the river flowing through the vegetated areas had not
reduced but rather widened in some reaches (M1 and M2). The decrease in agricul-
tural land was mostly observed adjoining the rivers. Interestingly, the fallow land
was not reduced rather slightly increased by 4.96% from 1993 to 2017, and overall,
the open land decreased by 15.6% (1968–2017). The adjoining Siliguri showed the
negligible presence of vegetation from the beginning, and during this period, the
reduction of vegetation was also not very alarming (4.07%). The reduction measured
in the first half (3.67%), adjacent to B River in B1–B4, was largely compensated in
the second half (0.43%). A relatively large vegetation patch, adjacent to M8, was
gradually converted into housing. Surprisingly, tea gardens were increased (20.03%)
in the second half, after being reduced (11.99%) in the previous one, which might be
the reflection of seasonal cutting and replanting of tea or the ambiguity created by
similar spectral characteristics of the canopy cover of the trees planted in the tea
gardens to provide shade for tea plants. The estimated accuracy for these 1968, 1993,
and 2017 were 85.3%, 90.8%, and 91.2% with the kappa coefficient of 82.3, 88.5,
and 89.4. The highest accuracy was achieved for built-up with 93.5%, 94.2%, and
94.6% for 1968, 1993, and 2017, respectively.

3.2   Measurement of the Indicators

The indicators measuring anthropogenic intervention showed (Fig. 6.3, Table 6.5,
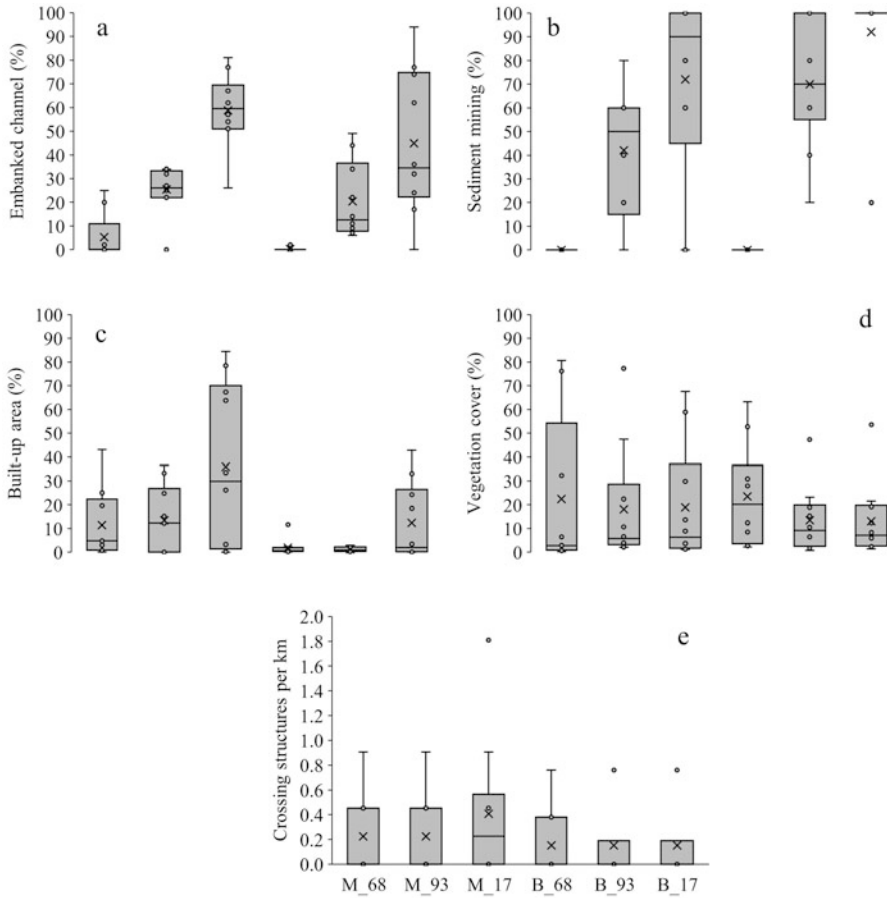Supplementary Table 6.1) a sharp change through time in most cases. At the

Fig. 6.3 The dynamicity of the indicators measuring anthropogenic interventions: (**a**) EM (%), (**b**) SM (%), (**c**) BA (%), (**d**) VA (%), and (**e**) CS (structures/km). (Figure prepared by the author)

beginning of 1968, the presence of concrete embankments (EM) and practice of in-channel sediment extraction (SM) was negligible, which in 49 years, increased to such an extent that more than half of the channel banks are now embanked (58.80% of M and 44.90% of B) and almost entire channel bed is under active sediment mining (72% of M and 92% of B). Since Siliguri is situated at the banks of M, therefore, it was heavily embanked to protect the urban setup. On the other side, B having a larger catchment area (287 km^2 compared with 116 km^2 of M) produces more sediment and hence more extracted. In 1968, negligible bank protection measures were identified in the reaches such as M8 and M9, but with time, embankments were built in the upstreams (M2–M6 and B5 and B6). Similarly, extraction from channel beds was initiated in the late 1980s in the reaches adjoining the Siliguri (M8–M10 and B8–B10) and expanded upstreams. Following this, the

Table 6.5 Measurements of the indicators, change detection, and test of significance for the overall system (S) and separately for Mahananda and Balason

Indicators	Overall System						Mahananda						Balason					
	1968	1993	2017	Change (%) (1968-2017)	t-test	df	1968	1993	2017	Change (%) (1968–2017)	t-test	df	1968	1993	2017	Change (%) (1968-2017)	t-test	df
EM (%)	2.63	22.90	51.85	1871.48	−8.649***	37	5.33	25.40	58.80	131.50	−9.105***	37	0.20	20.40	44.90	120.10	−4.682**	18
SM (%)	0.00	56.00	82.00	8200.00	−10.699***		0.00	42.00	72.00	7200.00	−5.660**		0.00	70.00	92.00	9200.00	−11.5**	
BA (%)	6.42	7.38	24.10	275.39	−2.532*		11.46	13.52	35.88	165.38	−2.030*		1.89	1.24	12.31	892.74	−1.993*	
VA (%)	23.04	15.77	15.94	−30.82	0.920		22.49	18.09	18.89	4.42	0.264		23.53	13.45	12.98	−3.49	1.243	
CS (structures/km)	0.19	0.19	0.28	47.37	−0.727	38	0.23	0.23	0.41	78.26	−0.861	38	0.15	0.15	0.15	0.00	0.000	
CA (km²)	25.08	23.03	14.94	−40.43	4.504***	37	8.31	8.57	6.32	−23.95	1.988*	37	16.77	14.46	8.62	−48.60	7.541**	17
CW (m)	482.24	450.54	291.55	−39.54	4.490***		408.92	343.31	271.89	−33.51	2.228*		548.24	557.77	311.21	−43.23	4.561**	
CL (km)	239.34	169.93	122.37	−48.87	4.213***		81.05	54.51	42.11	−48.04	−9.861**		158.29	115.42	80.26	−49.30	5.460**	
CCB (%)	80.55	74.66	71.94	−10.69	2.104*		75.82	68.78	68.71	−9.38	1.002		84.80	80.53	75.16	−11.37	2.436*	
BI	9.13	6.63	4.99	−45.35	4.148***		7.24	5.17	3.91	−45.99	2.025*		10.84	8.09	6.07	−44.00	5.698**	

* Significant at 95%; **Significant at 99%

BA was also expanded from 11.46% in 1968 to 35.88% in 2017 in the adjacent floodplain of M. For B, the initial BA was much lower than that of M, amounting to only 1.89%, which rose to 12.31% during this period. Since Siliguri was already urbanized in 1968, therefore reaches such as M8, M9, and M10 showed lower rates of increase than M3, M5, and M6 in the upstreams. Conversely, the upstreams of B were not at all urbanized, and the main agglomeration was seen in the lower reaches, adjacent to Siliguri urban region, namely B8, B9, and B10. Drastic decrease in vegetation cover (VA) was evident in the floodplains of both rivers, but the floodplains of M experienced a sharp decrease until 1993, which was further arrested and showed a slight increase from 1993 to 2017. But in the case of B, the trend was gradually declining. Overall, VA was decreased by 30.81%, which was even greater in the floodplains of B, measuring 44.83%. But the loss was concentrated in most of the upstream reaches such as M1, M2, M3, B1, B2, B3, B4, B5, and B6, since the lower reaches were already devoid of subsequent vegetation cover in 1968. In the beginning, there were only 8 bridges in the entire study region (4 on M and 4 on B), but those on M alone were gradually increased to 8 in later years. However, the CS on B remained constant during these 49 years. Most of the bridges were identified in the close vicinity of Siliguri (M7–M10 and B9) with a few adjacent to hills in M2 and B2.

A reversal of the sharp increase of anthropogenic interventions was observed in the measurement of planform properties (Fig. 6.4, Table 6.5, and Supplementary Table 6.2). The overall CA was reduced by 40.43%, and the rate was even higher in the case of B, amounting to 48.60% compared with a reduction of 23.95% in the case of M. Similarly, the overall CW was also heavily decreased by 39.54%, and the rate of this for B was higher (43.23%) than that of M. The rate of narrowing was mostly accelerated in the second half for both rivers. Most of the loss of CA and CW was observed in the reaches from M3 to M8 and for the entire B. Interestingly, M1 and M2, devoid of interventions, exhibited channel widening. Following the general trend, nearly half of the CL (48.87%) for the entire system was reduced during this period. While B had lost 49.30% of its CL, M being slightly on the lower side got reduced by 48.04%. Reaches such as M3–M8 along with B1–B4, and B6–B10 had experienced a relatively higher reduction of CL. As a result, this multi-threaded channel pattern had become single-threaded in many reaches. The reduction rate was much lower in the case of CCB. Overall, 10.69% of CCB was reduced. Contrary to this, CCB was increased in some of the reaches such as M1, M9, and M10. Following the reduced CL, BI was also reduced noticeably. The reduction rate was 45.35% for the whole system. Interestingly, in this case, the BI of M was largely reduced (45.99%) than that of B (44.00%). Relatively upstream reaches such as M2–M7 and B1–B4 and B6-B8 had experienced higher alterations regarding BI. In some reaches, the BI was reduced to such an extent that it resembled a pseudo-meandering channel.

Test of significance also proved the sharp increase of anthropogenic alterations and drastic decrease in the channel planform properties. Except for VA and CS, the
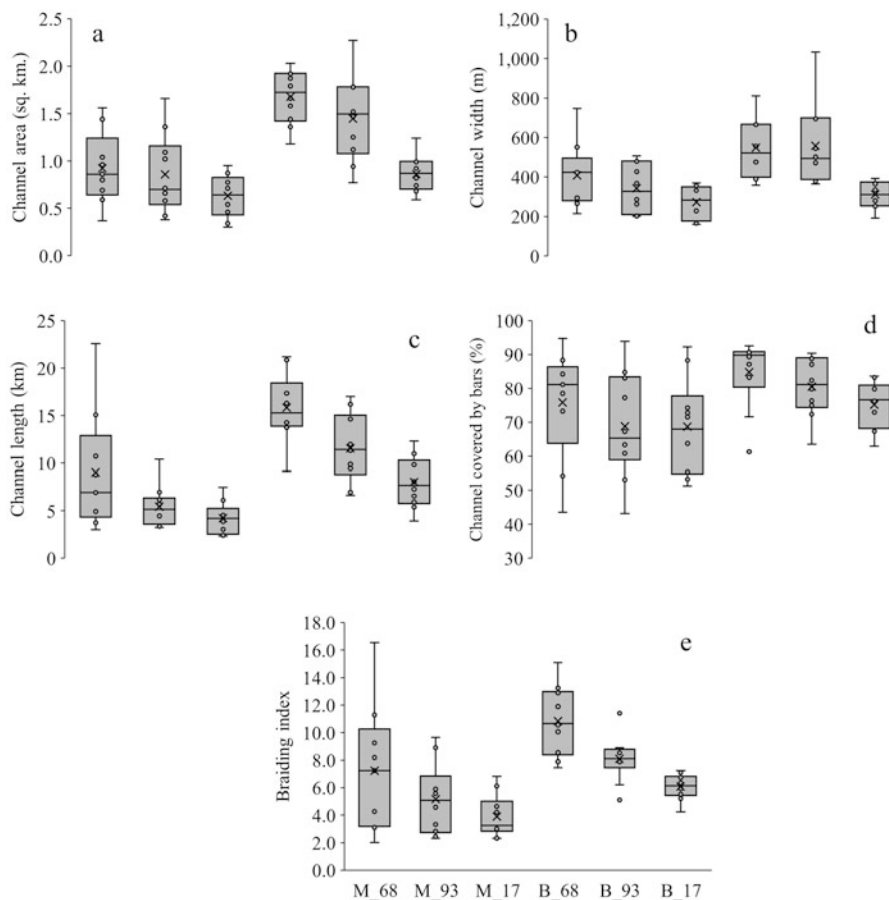
Fig. 6.4 The dynamicity of the indicators measuring channel planform properties: (**a**) CA (km^2), (**b**) CW (m), (**c**) CL (km), (**d**) CCB (%), and (**e**) BI. (Figure prepared by the author)

other three indicators, i.e., EM, SM, and BA, showed a significant increase from 1968 to 2017. Besides this, all the channel planform indicators, except CCB in M, showed a significant decrease during this period. B exhibited a higher level of significance than those of M for all these indicators.

3.3   Impact of Flood on Channel Modification

Inter-season comparison (Fig. 6.5, Table 6.6, and Supplementary Table 6.3) of channel planform properties revealed that in most cases, after the flood discharge, the measurements were increased. In between the pre- and post-flood season of
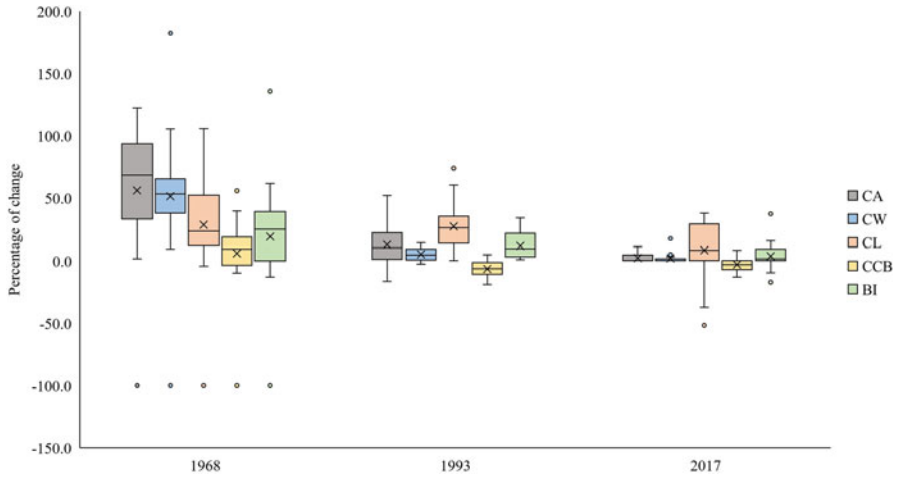
Fig. 6.5 Sharp decrease in inter-seasonal changes of the planform properties in 1968, 1993, and 2017. (Figure prepared by the author)

1968, overall CA, CW, CL, and CCB were significantly increased by 74.29%, 54.55%, 63.46%, and 14.71%. BI was also increased by 26.98% but not significantly since those increases were confined to a few reaches only. Marked changes on such a scale were completely absent in the later years, i.e., 1993 and 2017. The percentage of change mostly had become <10%, and even negative change of 4.5% and 3.15% was measured for CCB after the floods of 1993 and 2017, respectively. However, CL had increased by 33.67% between the pre- and post-monsoon of 1993, but most of this increase was insignificant, since they were restricted to a few reaches such as M4 and M6 and B4, B6, B7, and B8. The seasonal changes of B in 1968 were relatively more significant than those of M. During the initial year (1968), while CA, CW, CL, and CCB were significantly changed by the flood discharge in B, only the CA and CW were increased significantly in M. The percentage of change was also higher in B than in M. Despite being increased by 41.13%, the change of BI in M was not significant since it was confined in M4, M6, and M8. During the later years, no significant inter-seasonal changes in planform properties were observed. But among those, an increase of CL by 62.77% and BI by 24.88% in 1993 along with a reduction of CL and BI by 12.73 and − 6.68% in 2017 was noticeable.

3.4 Relationship Between Human Interventions and Channel Planform

It was observed from the calculated R^2 values (Table 6.7) that in the case of the whole system, all the planform properties showed high correlations with anthropogenic interventions. But when B and M were evaluated separately, some intersystem

Table 6.6 The indicator-wise measurements of channel planform for pre- and post-flood period along with their change detection and test of significance

Extents	Indicators	1968			1993			2017		
		Pre-flood	Post-flood	t-test (df)	Preflood	Post-flood	t-test (df)	Preflood	Post-flood	t-test (df)
S	CA	14.39	25.08	−2.955** (34)	21.26	23.03	−0.533 (38)	14.59	14.94	−0.240 (38)
	CW	312.02	482.24	−3.739** (34)	431.64	450.54	−0.306 (38)	286.15	291.55	−0.221 (38)
	CL	146.42	239.34	−2.283* (34)	127.13	169.93	−1.173 (36)	113.38	122.37	−0.532 (38)
	CCB	70.22	80.55	−2.094* (34)	78.18	74.66	0.783 (36)	74.28	71.94	0.650 (38)
	BI	7.19	9.13	−1.445 (34)	5.87	6.63	−0.950 (36)	4.83	4.99	−0.299 (38)
M	CA	5.52	8.31	−2.470* (17)	7.02	8.57	−0.931 (18)	6.14	6.32	−0.187 (18)
	CW	296.87	408.92	−1.688* (17)	318.31	343.31	−0.454 (18)	270.38	271.89	−0.039 (18)
	CL	64.81	81.05	−1.047 (17)	33.49	54.51	−1.527 (16)	48.25	42.11	0.691 (18)
	CCB	72.59	75.82	−0.400 (17)	68.46	68.78	−0.044 (16)	67.87	68.71	−0.442 (18)
	BI	5.13	7.24	−1.107 (17)	4.14	5.17	−0.914 (16)	4.19	3.91	0.350 (18)
B	CA	8.87	16.77	−2.652** (15)	14.24	14.46	−0.109 (18)	8.45	8.62	−0.198 (18)
	CW	333.66	548.24	−3.979** (15)	544.97	557.77	−0.146 (18)	301.92	311.21	−0.307 (18)
	CL	81.61	158.29	−2.402* (15)	93.64	115.42	−1.612 (18)	65.13	80.26	−1.351 (18)
	CCB	66.84	84.80	−3.667** (15)	85.96	80.53	1.639 (18)	80.69	75.16	1.679 (18)
	BI	10.14	10.84	−0.526 (15)	7.25	8.09	−1.227 (18)	5.48	6.07	−1.341 (18)

* Significant at 95%; **Significant at 99%
S system, *M* Mahananda, *B* Balason

Table 6.7 Estimated R^2 values for each planform parameter indicating the correlation between anthropogenic alterations and channel planform adjustment

Indicator	R^2(S)	R^2(M)	R^2(B)
Channel area in sq. km	0.811	0.939	0.729
Channel width in m	0.713	0.945	0.606
Channel length in km	0.849	0.778	0.889
Reach covered by bar (%)	0.738	0.896	0.458
Braiding index	0.807	0.820	0.790

differences were identified. For the whole system, all the channel planform indicators showed a high correlation with an R^2 value of over 0.700. The correlations of CL, CA, and BI were even higher with an R^2 value of >0.800. Intra-system comparisons between M and B revealed that the channel planform of M was more impacted by anthropogenic interventions than that of B. While all the channel planform indicators were measured with R^2 values of >0.750 at M, only BI was correlated with an R^2 value of >0.750 at B. The CCB has not even showed significant correlations with the ongoing anthropogenic interventions. Therefore, it was affirmed that the dynamicity of channel planform was profoundly explained by the selected variables of anthropogenic intervention. However, the reduction of bars remained less explained. This statistical analysis clearly explains that the anthropogenic interventions in the form of embanking, sediment extraction, and landscape alteration have significantly affected the planform attributes. The rivers were noticeably narrowed; their channel length was lost, which ultimately altered them from wide multi-threaded, braided channels to single-threaded sinuous ones. Since anthropogenic interventions were recently intensified in the floodplains of Balason, therefore, it had still managed to retain its intrinsic equilibrium, which was already lost for Mahananda due to remarkable alterations at its floodplain for a long time.

4 Discussions

4.1 Spatiotemporal Pattern of Anthropogenic Interventions and Planform Modification of MBS

It was revealed from the LULC analysis that the areal coverage of impervious surfaces had increased significantly in the past 49 years by engulfing the adjoining rural areas. The rate of urbanization was relatively less in the first half (1968–1993), but the adoption of new economic policies in 1991 by the Government of India had accelerated the growth of Siliguri in the second half (1993–2017) (Datta, 1998, 2003; Debnath et al., 2017; Ghosh, 2018, Ahluwalia, 2019). New development policies had increased the economic potency of the Siliguri, and to take advantage of that, people in large numbers from the adjoining areas immigrated to this region. With increasing population, an increase in impervious areas became inevitable, and thus, Siliguri urban region had expanded in such an ill-planned manner by creating enormous pressure on natural resources, especially riverine resources.

Fig. 6.6 Glimpses of ongoing anthropogenic interventions in the study area: (**a**) large embankments with groynes and bed stabilization structures along the banks of M, (**b**) intensive sediment extraction from the B river bed, (**c**) encroached banks of M, and (**d**) bridge pillars altering the flow of M. Pictures were taken by the author in December 2016 and April 2017. (Figure prepared by the author)

Measurements of the anthropogenic indicators exhibited exact accordance with this expanding urbanization. Urbanization or concretization needs loads of construction aggregates, which are mostly fulfilled by extracting riverine sediments (Fig. 6.6). The MBS had experienced a similar phenomenon since the late 1980s (Mitra et al., 2020). Initially, a notable portion of the immigrated populace had chosen sediment extraction from rivers as their livelihood and started living adjacent to the extraction sites, mostly at the river banks. Thus, areas alongside both rivers were mostly encroached and converted into built-ups. Now to provide a safe allocation of their newly built dwellings, embankments were introduced (Fig. 6.7). Earlier, the riverbanks adjoining the main city region and the bridges were embanked, but now with increasing settlements, the adjacent river banks were also embanked. Now with the accelerated urbanization, the need for the riverine sediments started increasing, and to meet that demand, extraction activities had occupied nearly the entire unconfined stretch of MBS. Following the emergence of the Siliguri urban region, further immigration had taken place, which in return again escalated the intensity of urbanization, embanking, and sediment extraction. Expanded urban areas need ease of access, and to provide that, several bridges were introduced, and the pillars of those being situated at the river beds eventually altered the discharge. Coupled
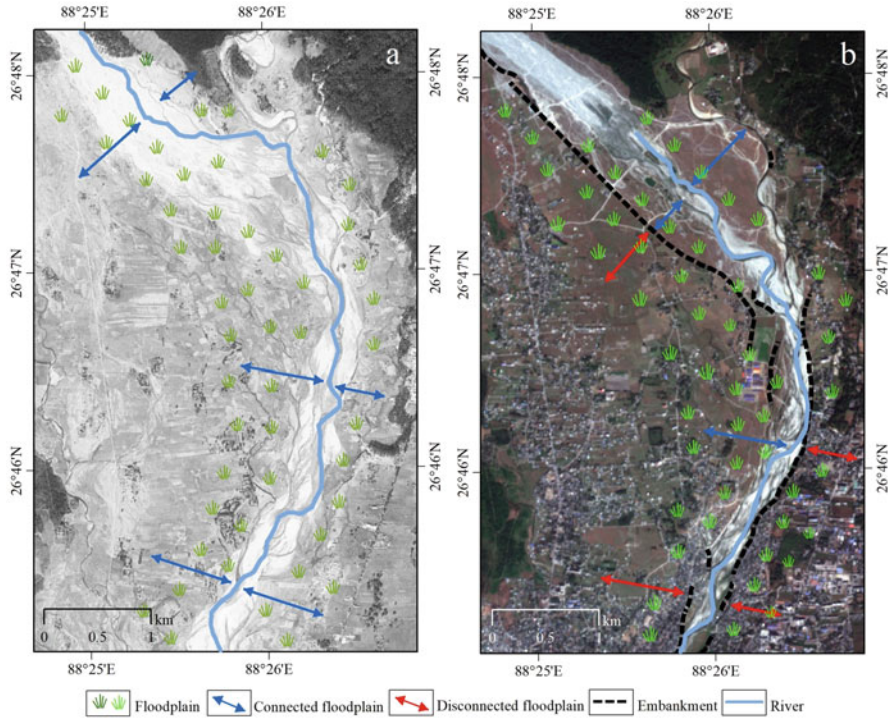
Fig. 6.7 Concretized embankments are laterally disconnecting the river from its floodplain and narrowing the channel corridor: (**a**) planform in 1968 with no embankments and laterally connected floodplains of M and (**b**) planform in 2017 with mostly embanked, laterally disconnected and narrowed. (Figure prepared by the author)

effects of these ultimately resulted in the loss of naturalness of this river system and the region.

In response to this, channel planform started modifying and ultimately pushed to such an extent that regaining its intrinsic equilibrium become mostly unachievable (Fig. 6.8). The predominance of the impervious areas in the adjoining floodplains made the runoff free from sediment load, and protected embankments prevented the lateral migration of the river. Along with these, extraction of sediment from the channel bed helped in initiating channel incision. Now, coupled effect of these would eventually increase the erosion potentiality of the river, which in return made the river system narrower, incised, and ultimately the whole drainage pattern became altered. It was evident that during this period, significant alterations had happened, which were relatively higher in the case of B than M. The adjoining of M was urbanized, and the banks were embanked from several decades earlier; however, B had experienced such interventions at a later stage. So it can be understood that to some extent, the channel pattern and hydraulics of M had adjusted with these interventions. Interestingly, the upper reaches of M, covered by dense natural vegetation, portrayed noticeable channel widening. Other than that, most of the
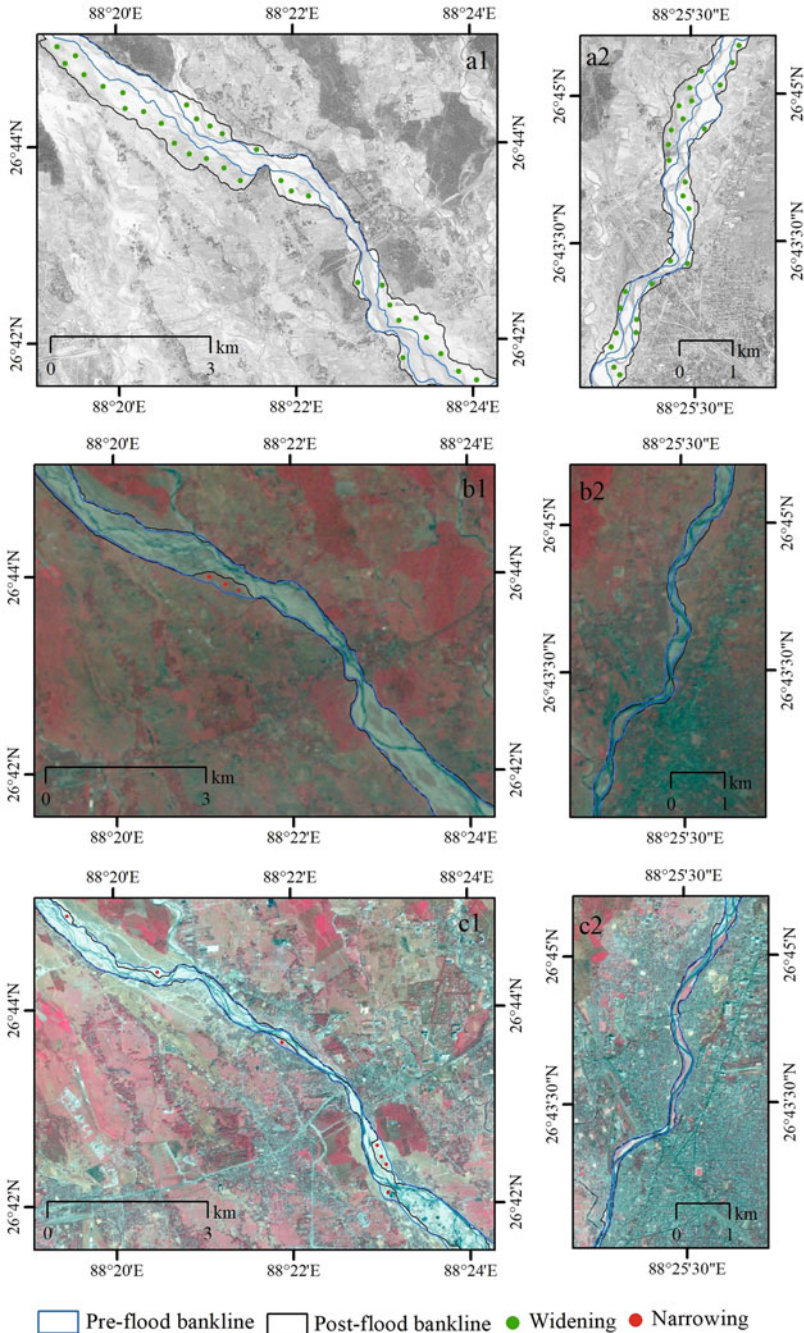
Fig. 6.8 Channel narrowing through time along with pre and post-flood changes in bank lines: (**a1** and **a2**) conditions of B and M in 1968 is showing extensive widening after the flood, (**b1** and **b2**) conditions of the same in 1993 is showing nearly no widening but slight narrowing after the floods, and (**c1** and **c2**) intensively narrowed river reaches of B and M in 2017 along with notable narrowing after the floods. (All of the used images were post-flood images and the figure was prepared by the author)

reduction of the channel planform properties was observed in relatively upstream reaches of the main urban region, and the spatial extent of those was found in exact accordance with increasing interventions. During the study period, there was hardly any sudden and intensive tectonic event; changes in rainfall patterns or other events that can control the channel pattern were observed in the studied region (Mitra et al., 2020). Therefore, it can be affirmed that the ongoing rapid changes regarding channel planform are being significantly controlled by ongoing anthropogenic interventions.

4.2 Comparing the Role of Flood and Human Activities on Planform Modification

It is evident from the analysis that in the studied system, anthropogenic interventions are predominantly controlling the channel planform adjustments. Anthropogenic activities had increased through time and in response to that channel planform had adjusted to such an extent that even high flood discharges could not significantly alter the planform (Fig. 6.8). Inter-seasonal measurements of the planform indicators exhibited that except for 1968, other years did not show significant changes; however, some of the changes were notable in those years but confined to a few reaches. As mentioned earlier, the selected years were characterized by large-scale floods across northern West Bengal, but despite that, only the changes in 1968 were found significant. It was also evident that the post-flood changes were gradually becoming more diminishing in the later years (1993 and 2017). At present, a significant portion of the study reach is embanked by huge concrete embankments; the height of those is even exceeding 13 m. So when the storm flux sets in, the excess water cannot be spilt in the floodplains, which triggers the down-cutting process. Sediment-free runoff from the impervious landscape and intense sediment extraction from the channel bed fuel this process. So eventually, storm flux or monsoonal discharge, instead of helping to regain the river's intrinsic channel pattern, ended up enkindling the incision and narrowing process. Among the indicators, the seasonal change of BI was not significant for these years. Several reaches had even experienced a decrease in seasonal change of BI, indicating the reduction of bars and channel length.

The superimposition of the HFLs on the present cross-sections (Fig. 6.9) depicts that most of the sites are protected with such huge embankments that even a flood-like 1968 cannot overtop it. Areas such as Airview more, where the river can spill its water, are now being embanked also, and the remaining chances of lateral migration and spilling of flood discharge are being reduced at an alarming pace. So with such rapid anthropogenic interventions, channel modification due to floods is becoming negligible.
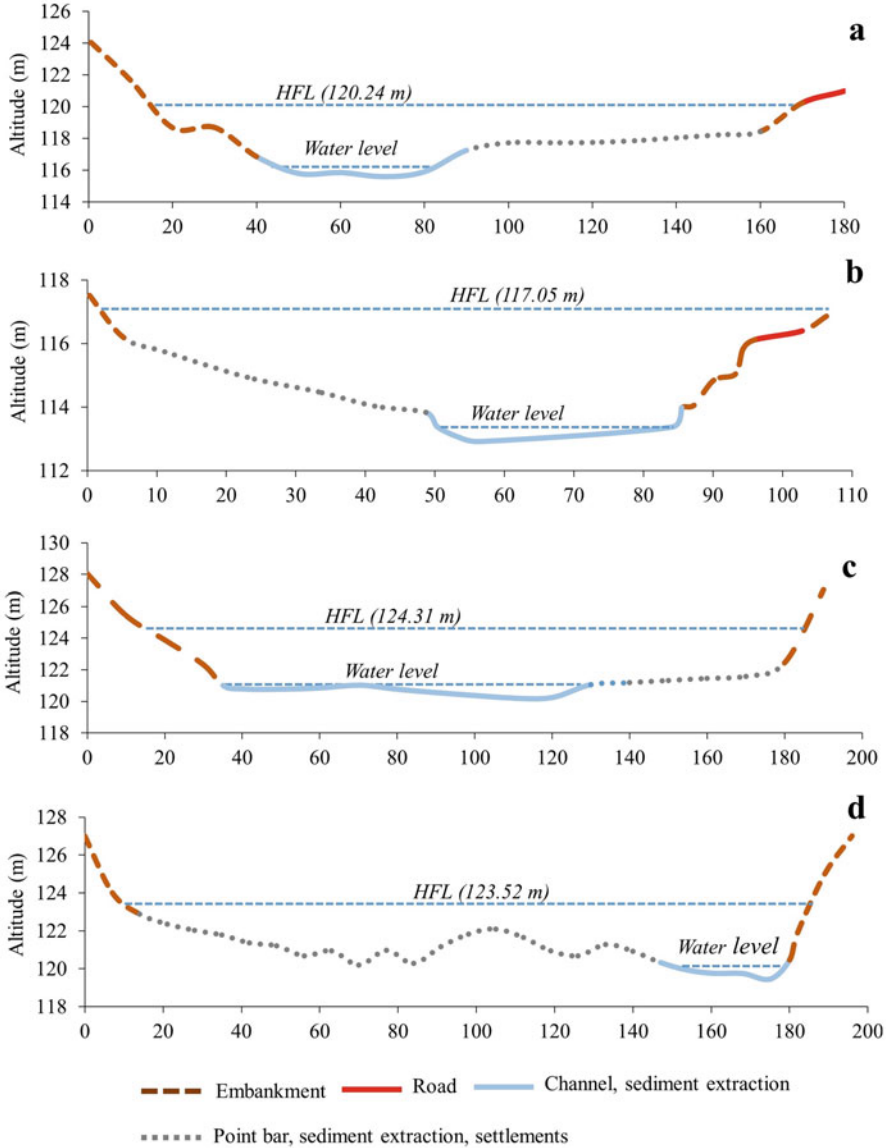
Fig. 6.9 Superimposition of the HFL (1968 flood level) on the present cross-section shows in most of the reaches embankments are so high that they can be hardly overtopped even with the largest scale of flood discharge in the recorded history. The cross-sections are situated at (**a**) Champasari (M7), (**b**) Airview more (M8), (**c**) Matigara-Balason bridge (B9), and (**d**) Matigara-Balason Railway bridge (B9). (Figure prepared by the author)

4.3 Possible Future Pattern of Channel Planform and Its Effects

If anthropogenic interventions and planform alteration would continue at this pace, then there will be an irreparable alteration regarding channel pattern. Along with this, the entire system would experience severe undersupply of riverine resources and related hazards in the socio-hydrological domain. Initial tendencies are indicating this. Already the channel flowing through the main urban region has become single threaded, and this tendency is spreading upstream. Interviews with the local mining workers have highlighted that the lowermost reaches of these systems are experiencing insufficiency regarding sediments of the required grade. Excessive extraction in the past had deteriorated the condition. The upper reaches will experience this in near future as at present those are being extracted extensively to compensate for the nonavailability in their lower counterparts. Increased sediment extraction from the upstreams has further fueled the embanking and urbanization. Coupled effect of these has started reconfiguring this broad, multi-threaded, braided river system into a narrower, single-threaded, and sinuous one. It was observed during the field visit at Matigara and Champasari that secondary bank protection measures are being introduced. This will further restrict the rivers from lateral migration during the heavy seasonal discharge. With such intense human activities, incisions become inevitable. According to Mitra et al. (2020), the unconfined M and B had experienced >2 m of an incision during 1987–89 to 2019, which was similar to Tamang and Mandal (2015).

Reshaping of the rivers in the unconfined floodplains would have an impact on the entire system such as incision tendencies can migrate upstream and accumulation of sediments in the debouching areas can increase. The recharge–discharge cycle of groundwater also is being disturbed as incised river channels have a lower level than the vadose zone; therefore, recharge of that zone from river water has become impossible (Fig. 6.10). On the other side, the groundwater table maintains an equilibrium with the water level of the nearby river; now if the water level of that river goes down, the groundwater level should go down to maintain that equilibrium. The floodplain region of M7–M8 and B5–B9 is experiencing similar problems where the continuous discharge of vadose water can be seen along the river banks, and as a result of that, the non-monsoon lack of groundwater is becoming prominent (Biswas, 2016). Furthermore, the finer particles released during the sediment extraction can also clog the pores, which will obstruct the hyporheic exchange. Finally, the living biota, especially fishes, will suffer enormous habitat destruction. Fishes of these rivers are mostly benthopelagic, bottom feeders, and live in shallow rivers with a rocky or sandy bottom and higher currents. Now with such alteration in channel planform, all these preferable living conditions shall be altered, which will ultimately reshape the biotic assemblage of these river systems. Personal interviews with fishermen supported this notion as they confirmed the large-scale lowering of consumable fishes, observed by Paul et al., 2009.

Fig. 6.10 Problems associated with channel adjustments: (**a**) recent incision noticed on B in December 2017, (**b**) signs of bed lowering on B at Matigara Railway bridge, (**c**) destabilized bridge pillar on M at Champasari, and (**d**) discharge of vadose water noticed from the black clay layer along the banks of B. Pictures were taken in December 2017 by the author. (Figure prepared by the author)

5   Conclusion

After analyzing the results, it can be affirmed that the unconfined stretch of the MBS is undergoing planform alterations at an alarming pace. Analysis of the anthropogenic interventions and inter-seasonal fluctuations in channel planform properties also exhibit that as the intensity of human activities is increasing, the effect of flood on channel planform is diminishing. As a result of that, the river is steadily losing its inherent equilibrium condition or the river is becoming narrower and sinuous, and showing no tendencies of reshaping with even large-scale flood discharge. The channel is embanked to such an extent that even the discharge of the HFL will not overtop them. Intensive sediment extraction has disturbed the sediment budget, which leads to undersupply of the required sediment grade. Now with less bed load, the river has started down cutting and flood discharge with high energy is fueling that process. Therefore, the incised river shall further become narrower, and ultimately irreparable adjustments regarding channel planform would become inevitable. This may bring imbalance in the socio-hydrological domain regarding lack of groundwater, loss of jobs due to insufficiency of riverine resources, and risking the

road network connectivity. To overcome this, immediate restoration activities should be started in the form of halting any new embankment building, freeing the modern floodplains from settlements, imposing strict regulations on sediment extraction, and afforesting the adjoining areas, especially bank lines.

Floods being the most important natural channel-forming factor eventually act as a feedback mechanism for the channel planform, since it helps the river planform to regain its intrinsic equilibrium condition. Along with this, it also cleans the river, provides sediments to the channel bed, nurtures the riparian zone, adds minerals to the soil of the floodplain and nutrition to the river water essential for the biota, and enormously recharges the groundwater. Now with such intensive anthropogenic activities, flood discharge cannot perform most of these ecosystem services. Along with this, if the flood discharge starts altering the planform in the way how human intervention alters, then it shall permanently modify the channel planform, which will be hazardous for its stakeholders and the present tendencies are indicating this.

Appendix

Supplementary Table 6.1 Indicators of anthropogenic interventions measured reach-wise and change detection (1968–2017) in %

R_ID	EM_68	EM_93	EM_17	Change (%) (68–17)	SM_68	SM_93	SM_17	Change (%) (68–17)	BA_68	BA_93	BA_17	Change (%) (68–17)	VA_68	VA_93	VA_17	Change (%) (68–17)	CS_68	CS_93	CS_17	Change (%) (68–17)
M_1	0.0	0.0	26.0	2600.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	80.7	77.3	58.9	−27.0	0.0	0.0	0.0	0.0
M_2	1.0	22.0	54.0	5300.0	0.0	0.0	0.0	0.0	3.0	0.0	0.2	−93.2	76.1	47.4	67.6	−11.2	0.5	0.5	0.5	0.0
M_3	0.0	25.0	51.0	5100.0	0.0	40.0	100.0	10000.0	0.9	0.0	3.2	255.5	32.3	22.4	29.9	−7.5	0.0	0.0	0.0	0.0
M_4	0.0	22.0	57.0	5700.0	0.0	40.0	100.0	10000.0	0.7	0.8	1.8	166.0	6.4	10.7	13.6	112.4	0.0	0.0	0.0	0.0
M_5	0.0	27.0	62.0	6200.0	0.0	60.0	100.0	10000.0	6.1	12.5	26.2	328.5	2.8	4.8	8.9	214.5	0.0	0.0	0.0	0.0
M_6	0.0	34.0	77.0	7700.0	0.0	80.0	100.0	10000.0	4.8	15.1	67.3	1316.3	0.7	2.2	1.2	82.7	0.0	0.0	0.0	0.0
M_7	2.0	25.0	81.0	3950.0	0.0	60.0	80.0	8000.0	25.0	33.3	84.5	237.9	0.2	3.5	2.1	1055.0	0.5	0.5	0.5	0.0
M_8	25.0	32.0	67.0	168.0	0.0	60.0	60.0	6000.0	43.1	36.5	78.5	82.1	0.9	3.9	1.9	109.5	0.9	0.9	1.8	100.0
M_9	20.0	33.0	51.0	155.0	0.0	60.0	80.0	8000.0	19.7	24.8	63.7	224.2	2.3	6.6	1.2	−49.5	0.0	0.0	0.5	450.0
M_10	NA	34.0	62.0	NA	NA	20.0	100.0	10000.0	NA	12.2	33.5	NA	NA	2.1	3.7	NA	0.5	0.5	0.9	100.0
B_1	0.0	8.0	24.0	2400.0	0.0	20.0	20.0	2000.0	0.0	2.1	0.0	0.0	27.9	15.2	19.2	−31.4	0.4	0.0	0.0	−100.0
B_2	0.0	9.0	17.0	1700.0	0.0	40.0	100.0	10000.0	0.5	1.6	0.3	−32.2	31.1	18.9	21.5	−30.9	0.4	0.8	0.8	100.0
B_3	0.0	6.0	6.0	0.0	0.0	60.0	100.0	10000.0	0.4	0.8	0.0	−90.4	52.7	47.3	53.5	1.6	0.0	0.0	0.0	0.0
B_4	0.0	7.0	36.0	3600.0	0.0	60.0	100.0	10000.0	0.2	0.3	0.3	70.7	63.2	23.1	12.3	−80.5	0.0	0.0	0.0	0.0
B_5	0.0	22.0	74.0	7400.0	0.0	60.0	100.0	10000.0	0.9	0.1	0.4	−53.5	30.9	7.8	2.6	−91.4	0.0	0.0	0.0	0.0
B_6	0.0	34.0	77.0	7700.0	0.0	80.0	100.0	10000.0	0.4	0.4	3.4	777.1	12.3	1.7	2.3	−81.0	0.0	0.0	0.0	0.0
B_7	0.0	11.0	32.0	3200.0	0.0	80.0	100.0	10000.0	1.8	0.8	18.5	939.2	8.5	2.8	1.4	−83.9	0.0	0.0	0.0	0.0
B_8	0.0	14.0	33.0	3300.0	0.0	100.0	100.0	10000.0	2.3	0.9	42.7	1766.3	3.8	6.5	8.3	117.2	0.0	0.0	0.0	0.0
B_9	2.0	49.0	62.0	3000.0	0.0	100.0	100.0	10000.0	11.6	2.6	33.1	184.6	2.7	10.5	6.0	124.6	0.8	0.8	0.8	0.0
B_10	0.0	44.0	94.0	9400.0	0.0	100.0	100.0	10000.0	0.8	2.9	24.3	2894.5	2.2	0.7	2.7	24.9	0.0	0.0	0.0	0.0

Supplementary Table 6.2 Indicators of channel planform measured reach-wise and change detection (1968–2017) in %

R_ID	CA_68	CA_93	CA_17	Change (%) (68–17)	CW_68	CW_93	CW_17	Change (%) (68–17)	CL_68	CL_93	CL_17	Change (%) (68–17)	CCB_68	CCB_93	CCB_17	Change (%) (68–17)	BI_68	BI_93	BI_17	Change (%) (68–17)
M_1	0.4	0.7	0.9	135.1	214.3	286.4	347.1	62.0	3.0	7.0	7.5	147.5	81.1	83.0	88.3	8.8	3.2	6.2	6.8	110.8
M_2	0.7	1.0	0.7	2.9	266.1	426.9	342.3	28.6	6.9	4.6	5.0	−28.3	94.8	93.9	92.3	−2.6	9.3	5.9	6.1	−33.9
M_3	1.6	1.7	1.0	−39.1	550.8	486.7	370.2	−32.8	15.1	4.5	2.6	−82.8	88.3	84.7	72.8	−17.6	11.3	8.9	4.6	−58.9
M_4	1.4	1.4	0.8	−46.3	747.5	479.2	356.2	−52.3	22.6	10.4	6.1	−73.0	84.2	77.2	71.5	−15.0	16.5	9.7	3.2	−80.4
M_5	1.0	0.7	0.6	−45.2	439.0	368.3	235.3	−46.4	10.7	6.2	4.5	−57.6	78.5	63.3	63.7	−18.8	8.2	5.6	4.2	−48.6
M_6	1.0	0.7	0.5	−52.1	423.3	262.9	228.4	−46.0	8.8	5.7	3.0	−65.4	73.3	67.3	53.3	−27.2	7.2	4.6	3.2	−56.5
M_7	0.9	0.4	0.3	−60.5	440.9	211.6	165.3	−62.5	5.3	3.6	2.3	−56.6	84.3	60.8	55.4	−34.4	4.3	2.8	2.3	−45.6
M_8	0.8	0.4	0.3	−62.5	304.6	202.3	159.9	−47.5	4.9	3.4	2.4	−51.1	54.3	53.1	51.2	−5.5	3.1	2.5	2.3	−25.1
M_9	0.6	0.6	0.5	−8.5	293.9	202.2	181.8	−38.1	3.7	3.2	3.9	4.0	43.6	43.2	64.4	47.8	2.0	3.3	3.0	49.8
M_10	NA	1.1	0.8	NA	NA	506.8	332.5	NA	NA	6.0	4.8	NA	NA	61.3	74.2	NA	NA	2.3	3.3	NA
B_1	1.2	0.8	0.7	−37.3	358.9	390.1	287.6	−19.9	13.7	9.9	7.3	−46.9	89.4	87.1	72.9	−18.4	10.1	8.8	5.5	−45.1
B_2	1.4	0.9	0.7	−52.8	555.7	365.4	279.7	−49.7	9.1	6.6	3.9	−57.1	91.5	72.4	62.9	−31.2	7.9	5.1	4.3	−46.1
B_3	1.9	1.5	1.0	−49.0	403.3	501.4	365.5	−9.4	16.3	6.9	6.5	−59.8	90.6	82.3	79.9	−11.9	10.6	8.5	5.9	−43.8
B_4	1.8	2.3	0.9	−48.6	389.9	1033.2	334.8	−14.1	17.6	16.2	9.8	−44.4	90.6	88.8	83.6	−7.7	11.9	11.4	6.7	−43.3
B_5	1.9	1.5	1.0	−46.0	666.2	486.4	380.4	−42.9	13.9	11.3	12.3	−11.4	90.3	76.3	76.2	−15.6	10.8	7.9	7.2	−32.7
B_6	2.0	1.8	0.9	−54.7	668.5	694.6	371.8	−44.4	20.8	17.0	10.1	−51.7	92.6	79.8	77.1	−16.7	12.9	8.1	6.6	−49.1
B_7	1.9	1.1	0.7	−63.0	811.2	544.3	252.5	−68.9	21.2	14.6	11.0	−48.2	87.1	63.5	68.5	−21.5	15.1	8.9	7.1	−53.0
B_8	1.6	1.8	0.6	−62.7	475.9	378.2	192.4	−59.6	17.3	12.0	5.9	−65.9	83.2	75.0	67.3	−19.1	13.2	6.2	5.2	−60.6
B_9	1.4	1.3	0.8	−39.7	487.5	471.6	255.2	−47.7	14.0	11.5	5.4	−61.6	61.3	89.8	80.1	30.7	7.5	7.9	5.8	−22.3
B_10	1.7	1.6	1.2	−25.3	665.2	712.6	392.5	−41.0	14.2	9.4	8.1	−43.3	71.5	90.4	83.2	16.3	8.5	8.1	6.4	−25.6

Supplementary Table 6.3 Reach–wise inter-seasonal change of planform properties

R_ID	Seasonal change (%)														
	CA_68	CA_93	CA_17	CW_68	CW_93	CW_17	CL_68	CL_93	CL_17	CCB_68	CCB_93	CCB_17	BI_68	BI_93	BI_17
M_1	42.31	1.47	7.41	58.00	5.45	1.73	-4.44	51.75	-14.47	2.43	-7.70	7.19	-9.24	1.89	-9.43
M_2	68.29	30.77	2.90	9.33	7.10	0.73	14.00	NA	-37.14	-2.54	NA	5.71	3.35	NA	-16.73
M_3	83.53	44.35	1.06	47.96	8.47	0.34	36.32	NA	-51.68	-6.28	NA	0.28	31.78	NA	0.60
M_4	56.52	19.30	9.01	42.11	8.34	1.45	58.05	73.91	0.99	18.19	-9.35	1.85	46.50	18.26	-1.52
M_5	103.92	14.52	1.79	25.68	10.41	0.15	46.65	26.80	31.59	-4.68	-12.45	-8.28	29.06	3.04	-17.07
M_6	113.33	29.41	4.55	50.69	14.51	0.02	22.73	60.45	3.40	-9.85	-3.03	-6.87	135.83	22.46	1.29
M_7	120.51	23.53	0.00	65.30	6.97	0.00	10.10	26.83	0.00	16.47	1.98	0.00	31.48	34.31	0.00
M_8	122.22	52.00	0.00	39.92	9.65	0.00	31.47	15.46	0.00	5.26	-14.72	0.00	48.80	5.60	0.00
M_9	34.09	13.73	0.00	65.68	11.54	0.00	3.32	14.08	0.00	11.29	4.75	0.00	1.52	9.04	0.00
M_10	NA	4.81	0.00	NA	2.31	0.00	NA	1.35	-8.19	NA	-9.46	8.22	NA	2.67	1.87
B_1	NA	4.05	0.00	NA	0.42	0.00	NA	0.10	6.28	NA	-1.30	-2.60	NA	0.88	11.74
B_2	NA	1.08	0.00	NA	0.52	0.00	NA	28.16	26.05	NA	-3.20	-3.65	NA	10.37	9.25
B_3	NA	-4.40	11.24	NA	1.02	1.17	NA	11.22	27.24	NA	-2.71	-5.18	NA	4.73	16.02
B_4	36.64	-2.16	4.55	36.09	11.36	6.79	105.83	25.91	20.37	22.11	-5.12	-5.18	61.77	23.89	13.28
B_5	3.31	-0.68	0.00	55.40	0.26	4.92	23.56	15.75	30.54	15.28	-7.28	-6.16	-1.19	12.07	8.87
B_6	32.68	1.13	0.00	55.18	-2.65	3.18	20.81	49.47	10.54	19.83	-10.24	-12.90	0.78	26.96	6.67
B_7	82.86	-16.42	4.41	182.44	0.77	17.75	42.50	29.96	25.09	55.92	-18.96	-11.51	5.94	21.74	0.85
B_8	79.55	14.10	0.00	53.36	3.56	0.00	59.76	30.85	38.08	39.73	-13.56	-10.63	25.14	10.11	5.25
B_9	1.49	17.92	0.00	81.67	0.69	0.00	21.09	13.60	29.95	7.04	-0.88	-2.67	-12.97	4.17	37.53
B_10	74.74	6.90	0.00	105.46	1.60	0.00	96.41	19.82	31.22	9.27	-1.30	-7.26	29.98	2.79	6.90

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